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TOPS: Technology options for coupled underground coal gasification and CO_2 capture and storage

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Abstract

The TOPS project takes a radical and holistic approach to coupled UCG-CCS, and thus the site selection criteria for the coupled processes, considering both geological, reservoir and process engineering aspects and different end-uses of the produced synthetic gas in order to optimise the whole value chain. In particular, the experimental research carried out utilises a newly constructed high pressure gasification reactor investigating several prospective options of UCG technology implementations. Integrated research addresses field based technology knowledge gaps, such as cavity progression and geomechanics, potential groundwater contamination and subsidence impacts, together with research into process engineering solutions in order to assess

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the role/impact of site specific factors and selected reagents on the operability of given CO_2 emission mitigation options. Ultimately, research aims to minimise the need for on-site CO_2 storage capacity as well as maximising the economic yield of UCG through value added end products.

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Keywords: Underground coal gasification; CO_2 capture and storage; site selection criteria; environmental impacts; life cycle assessment.

1. Introduction

In recent years, a number of researchers who considered combining underground coal gasification (UCG) with CO_2 capture and storage (CCS) as a potential option to mitigate against the climate change impacts of CO_2 emissions have suggested [1, 2, 3, 4, 5] that UCG creates unique opportunities for CO_2 storage in the post-gasification structures, coined as reactor zone carbon storage (RZCS).

As proposed, RZCS has some advantages, such as substantial apparent capacity (1,700- 4,500 tonnes CO_2 could be stored in the cavity of a single burn at 1,000 m depth and using a conventional geothermal gradient (30ºC/km), if 50% of that cavity were available); high permeability and injectivity; the potential for secondary coal adsorption storage, autoclosure through swelling of the coal; existing well set that could significantly reduce storage costs by 40-60%; potential for engineering control; potential to site within highly secure settings (coals beneath shales; seams at supercritical temperature and pressure conditions). However, the same researchers recognised that potential problems with cavity storage may outweigh its potential benefits, noting that the cavity itself is likely to be disturbed and may be difficult to characterise before CO_2 storage commences; that CO_2 is likely to interact with other coal gasification products complicating potential environmental impacts and that considering the inherent uncertainty in subsurface operations, could substantially complicate CO_2 storage efforts.

Most importantly, this storage potential, even if it were available, could be orders of magnitude smaller than the capacity required to store the CO_2 tonnage produced during the UCG process. Kempka et al. [6] and Nakaten et al. [7] point out that using CO_2 in subsequent processes may increase CO_2 the mitigation potential compared to applying geological CO_2 storage only. For instance, a feasibility study for UCG-CCS with coupled urea (fertiliser) production in the Jamalganji coal deposit located in Bangladesh demonstrates the potential re-use of 14.6 % - 18.6 % of the total CO_2 produced in the coupled process compared to that geologically stored in UCG voids (11.6 % - 16.3 %) at site-specific conditions. Supporting this argument, the Bulgarian UCG-CCS feasibility study indicates that only about 20.5 % of the CO_2 produced may be stored in the voids subsequent to a prospective UCG operation in the on-shore Dobroudzha coal deposit (Bulgaria) resulting from relatively low local geothermal gradients while using a conservative calculation approach (EU-RFCS project UCG&CO2STORAGE). Additionally, the potential CO_2 storage capacity would only be available after the end of the gasification operation, (i.e. the timeline of CO_2 production and storage capacity availability would not match), rendering on site coupled UCG-CCS rather difficult in many geological settings.

Over the past half century, coal gasification has been proven as a feasible process for utilising coal, with above ground gasification providing a precise process with the ability to control nearly every variable. In contrast, UCG relinquishes a significant degree of control for the ability to utilise coal without mining, while precision in this case comes from careful site selection aiming to ensure the quality and quantity of produced gas during the life of a project. Except for a recent study carried out by the Indiana University [8], which considers quantitative criteria for UCG assessment of Indiana coals, most early studies considered only the geological conditions for site selection and completely overlooked the subsurface engineering, panel design, reagent use and process engineering aspects, which control produced gas quality and the downstream processes that may lead to value added products beyond power generation [9, 10, 11, 12, 13]. In addition, the climate change impacts and the need to consider coupling the UCG and CCS have been ignored.

TOPS is an international research collaboration funded by the European Union's Seventh Framework Programme, which takes a radical and holistic approach to coupled UCG-CCS, and thus the site selection criteria for the coupled processes, considering both geological, reservoir and process engineering aspects and different end-uses of the produced synthetic gas, covering all options in order to optimise the whole value chain. One of the main objectives of the project is to develop a generic UCG-CCS site characterisation workflow, and the accompanying technologies, in order to minimise the need for on-site CO_2 storage capacity as well as maximising the economic yield of UCG through value added end products. Integrated research addresses field based technology knowledge gaps, such as cavity progression and geomechanics, potential groundwater contamination and subsidence impacts, together with research into process engineering solutions in order to assess the role/impact of site specific factors and selected reagents on the operability of given CO_2 emission mitigation options in a coalfield. The project benefits from a number of field UCG pilots which will operate during the project period and receive field data to use in modelling, as well as calibrating and validating the models developed. These pilots include:

- *Katowicki Holding Węglowy S.A. Wieczorek mine UCG pilot, Poland* - As part of a €8M national research consortium, Główny Instytut Górnictwa (GIG) is leading an *in situ* coal gasification project at 400 m depth at the Wieczorek Mine. Starting in June 2014, the first pilot-scale UCG experiment was conducted in Seam 501. In a period of two months around 250 tonnes of coal was gasified and around 900,000 m^3 of gas with a calorific value between 3.0 to 4.5 MJ/m^3 was produced. In the first instance, the produced gas was flared, however the long term plan is to utilise the gas for power. The process yielded syngas at around 600-800 m^3/hour with a gasification speed of around 200 kg/hour. The gas temperature at the outlet of the georeactor was measured as 470-520 ^oC. Current analysis includes the assessment of the impact of composition and efficiency of the supplied reagent (air-oxygen) on temperature and pressure in the reactor; the effect of the volume of water added to the reagent on produced gas quality; and the potential for the part supply of CO_2 as the reagent to produce carbon monoxide.
- *Coal mine Velenje UCG pilot, Slovenia* - As part of a €2.9M national research consortium, funded by the EU Regional Development Fund, Coal Mine Velenje has been carrying out a UCG feasibility study since 2011 and, after several site selection and design considerations, it was decided to run a UCG pilot in the upper coal seam, at 30 m depth close to the mine's Eastern license boundary. Two vertical wells are planned to serve as the reagent injector and production wells, connected by a horizontal well drilled from the surface. The heating value of coal varies between 4 and 8 MJ/kg. The hanging wall is clay, silty clay and partly sandy clay with no water-bearing Currently the mine is preparing the project documentation aiming at starting drilling in October 2014 and running a small scale UCG test in November 2014.
- *The Seamwell International Ltd YiHe Scoping UCG Plant in Inner Mongolia, China* - Under an exclusive joint venture partnership between Seamwell and the Chinese state-owned enterprise CECEP, Seamwell international is planning an experimental (scoping) plant to test and monitor the UCG process at around 450 m depth. Further analysis will include the environment around the gasifier, as well as the raw gas handling and a pilot scale power plant on the surface. Thus far, the project evaluated the coal seam resource, continuity across the coalfield, spatial distribution of calorific value and other UGC critical parameters using data from 94 exploration wells. Preliminary analysis of the reservoir rock properties were carried out using core samples collected from two recently drilled exploration boreholes by Seamwell.

2. Methodology and preliminary results

2.1 UCG site selection criteria and CO_2 storage capacity assessment

Combining CO_2 storage site selection options with UCG, the CO2QUALSTORE guideline [14, 15, 16], designed to provide a high level but systematic approach to the selection and qualification of sites and projects for CO_2 geological storage, is being used as a starting point. In addition, the project partners are utilising their experience and knowledge gained through a number of EU FP7 Energy Projects (such as SiteChar - Contract no: 256705) where research dedicated to the development of an integrated workflow for site characterisation, risk assessment and development of monitoring plans, representative of various geological contexts for CO_2 storage across Europe have been developed. When coupling UCG and CCS operations and considering UCG potential and CO_2 storage in appropriate storage formations within and close to a UCG license site, TOPS is using a two stage approach to site selection: during the first six months of the project, a high level geological qualification approach which is informed by the literature and the experience of the project partners was utilised and 43 different coal and field site based variables were identified. These included a wide range of coal properties, structural geology, hydrogeology, geotechnical and environmental properties. The second and novel phase of site selection criteria development will take place towards the end of the project, based on engineering processes such as reagent choice, panel design options, produced gas quality and downstream processes and gas utilisation, upon completion of the relevant research. This will inform the engineering design and economic criteria that are necessary for UCG.

The mapping of coal and coalbed methane (CBM) resources in the European area has gained significant interest in recent years and, in 2011 EU DG Energy funded the EuCoRes project aimed at providing a common classification and terminology for coal and CBM as well as a harmonised GIS database model integrating different data sources. The EuCoRes GIS database is made available to the TOPS project and towards its UCG and CO_2 storage capacity assessment work. In addition, significant relevant information on European coal resources and the corresponding GIS database is already available in the public domain through other sources [17, 18], Fig. 1.

a)

(b)

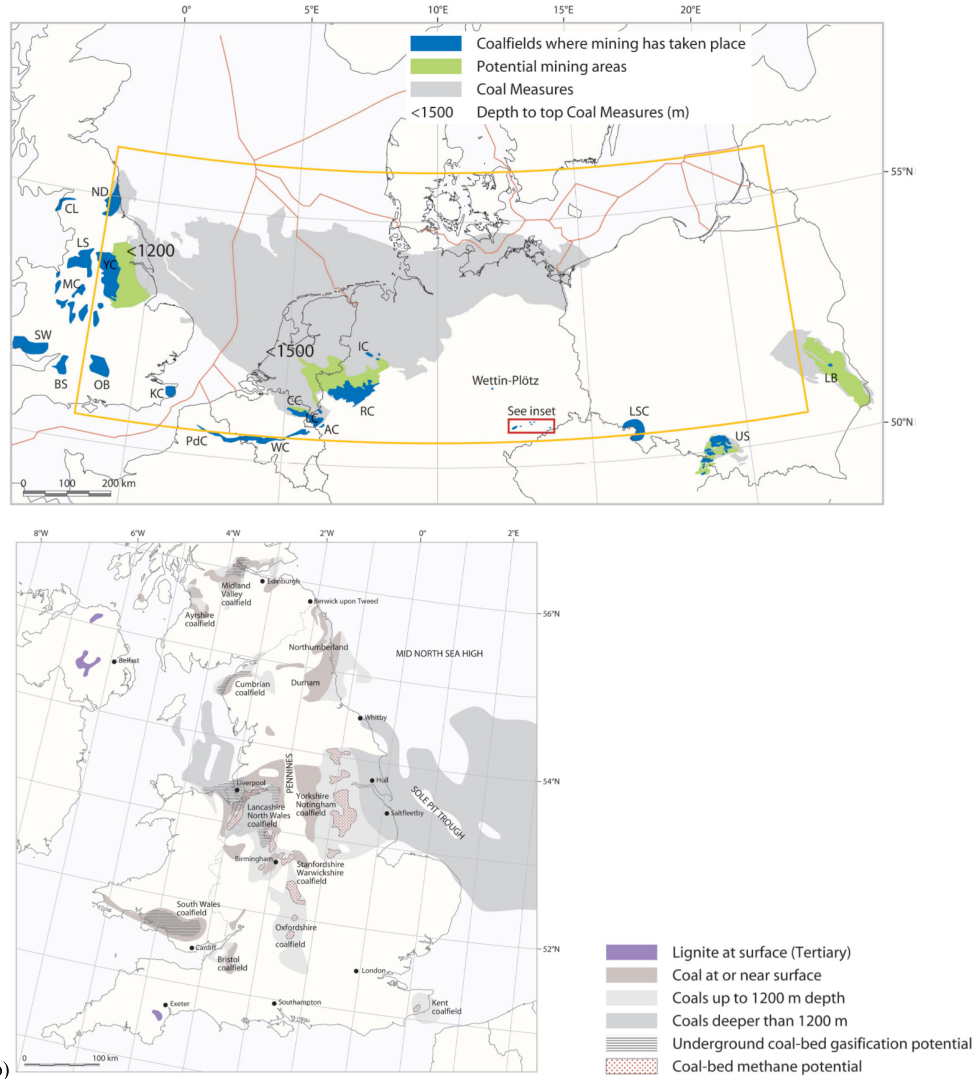


Fig. 1. (a). Carboniferous Coal Measures in the Southern Permian Basin Atlas; (b). The coalfields and coal-resource potential of the UK including UCG potential areas identified using simplified geological assumptions (modified after Gąsiewicz et al. [17]).

A number of projects funded by the European Commission, such as Joule II, GESTCO, GeoCapacity, CO2STOP have evaluated the CO_2 storage potential of saline aquifers, depleted hydrocarbon reservoirs and coal seams over several decades. The CO2STOP project aimed at providing a harmonised methodology to assess CO_2 storage capacity in Europe and provide estimates and geographical data for deep saline aquifers and hydrocarbon fields to be held in the EC JRC GIS database. These databases are currently being utilised by the TOPS project and the combined UCG – CCS potential in Europe is evaluated.

2.2 Thermochemical processes involved in UCG

In recent years, large scale laboratory experiments on coal gasification were reported by the China University of Mining and Technology [19, 20] and, more recently, by one of the TOPS partners Główny Instytut Górnictwa (GIG) in Poland [21, 22, 23, 24, 25]. Carried out at atmospheric pressures, these experiments and subsequent numerical modelling work investigated the thermo-chemical processes involved when different ranks of coal are gasified. However, until the TOPS project, none of the laboratory experiments operated the gasification process at realistic in-situ pressures whereby the reaction kinetics would favour alternative equilibrium concentrations. Furthermore, past experiments have mainly focused on the use of air or oxygen as the reagent and evaluated gasification performance under ambient conditions.

In contrast, the TOPS project utilises a newly constructed, unique and large scale high pressure gasification reactor which enables a comprehensive experimental programme to characterise the gasification process under varied coal, reagent use and pressures, simulating realistic subsurface conditions (Figs. 2 and 3). The new reactor can simulate UCG experiments at temperatures and pressures of up to 1600 ºC and 5.0 MPa respectively, using a number of reagents. Another innovative objective of the TOPS project is its approach to UCG-CCS site selection process by way of considering potential end uses of the produced gas with a view to balancing the need for CO_2 storage against value added end products and their transport to the markets. This option is being investigated through the use of different reagents such as air/oxygen enriched air, pure oxygen, oxygen/CO_2 mixture and hydrogen (hydrogasification) using two different coals. Liquid water and pre-heated steam will be evaluated as optional substrates. The target gasification products include low cost-low calorific value energy carriers (Energy Gas), synthesis gas generation of various compositions (Syngas), production of hydrogen rich gas (H_2) and generation of substitute of natural gas (SNG). The products obtained by selected UCG technology paths will be compared for costs and eco-efficiencies with alternative technologies such as shale and tight gas production later in the project.

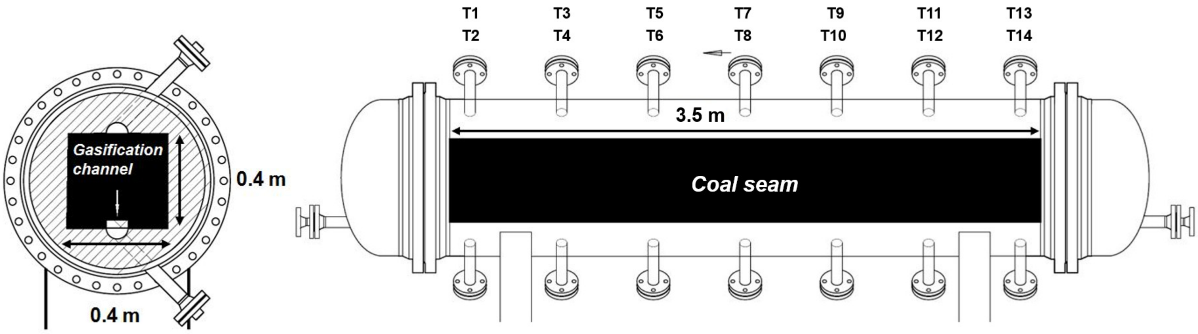
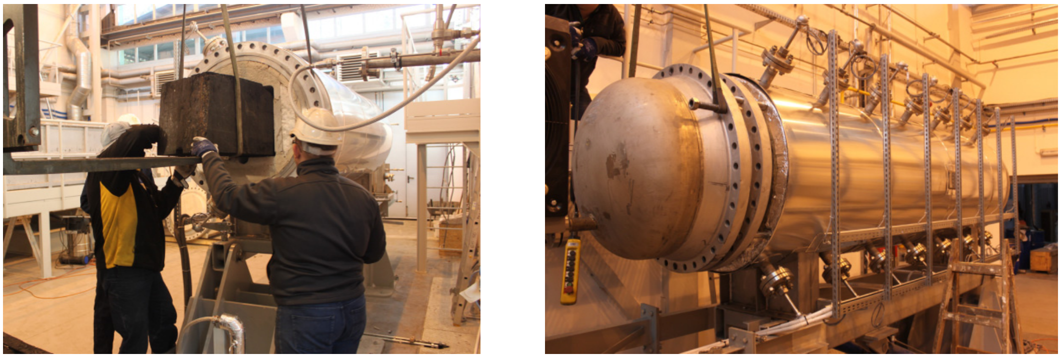


Fig. 2. Schematic of the high-pressure UCG reactor.

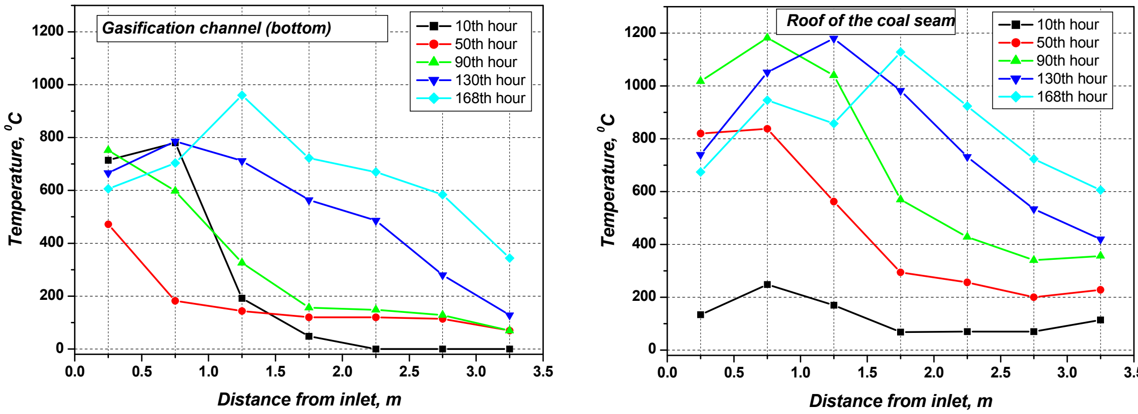
During the high pressure experiments, the produced gas is subjected to purification in the separation module. Partial gas stream is directed to the chemical analysis line where, after dehumidification and filtering, the main syngas components (H_2, CO, CO_2, and CH_4) are determined using gas chromatography. In order to control the gasification conditions and process development, the reactor is equipped with 14 high-temperature thermocouples (Pt10Rh–Pt), with 7 thermocouples located along the gasification channel and the remaining 7 along the roof of the coal sample (Figs. 2 and 3). Fig. 4 presents more recent results obtained from a 0.5 MPa air/oxygen enriched air gasification experiment using the new reactor.

In parallel with the laboratory experiments, process models are being set up in Aspen Plus© to improve the understanding of the gasification process at different reagent, coal type, pressure and temperature conditions. Laboratory data generated throughout the project will be used for model validation, and for the purposes of upscaling to field scale UCG operations.



(a) (b)

Fig. 3. Images of the high-pressure UCG reactor experimental set up.



(a) (b)

Fig.4. Temperature distribution (a) along the gasification channel and, (b) along the roof of the coal seam during a 0.5 MPa OEA-gasification experiment.

2.3 UCG cavity growth and control

UCG is a complex process involving interaction between in situ coal (with variable properties) and the injected reagents as well as with water that may flow into the cavity. The process involves fluid flows, heat and mass transfer, combustion and gasification with both heterogeneous and homogeneous reactions, together with the thermal geomechanics of the coal and surrounding strata. The principal mechanisms involved in the UCG process are mass transport, combustion, cavity growth and spalling. Simulation of UCG requires an integrated approach involving a Thermo-Hydro-Chemical-Mechanical (THCM) process. The most notable developments in cavity progression modelling are the CAVSIM model developed by Britten and Thorsness [26] at Lawrence Livermore National Laboratories and the two dimensional computational flow dynamics model developed by Perkins [27].

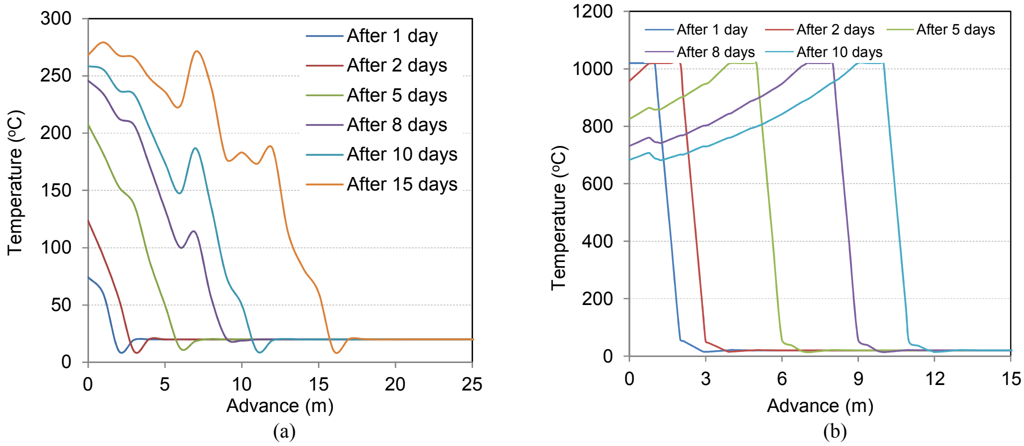


Fig. 5. Predicted temperature profiles (a) three metres in to the roof rocks and, (b) inside the gasification chamber.

Currently, the TOPS project is building both reactor and coalfield scale UCG models using thermo-chemical and hydro-thermo-mechanical modelling as required. Fig. 5 presents the estimated roof rock and gasification chamber temperature profiles obtained for a 20 m wide UCG panel in a 5 m thick seam at around 400 m depth using representative coal and rock properties from the field. The model runs represent the first 15 days of the gasification process with an estimated advance rate of 1 m/day.

2.4 Assessment of environmental impacts and risks

Research into the environmental impacts and risks associated with UCG includes groundwater protection and pollution evaluation, surface subsidence prediction and mitigation, and contingency planning. To this end, a Generic Environmental Risk Assessment Framework (GERAF) is being developed, which will comprise a software package with supporting documentation to guide managers and regulators through the project planning process, assisting in identifying data collection requirements and providing specific advice on how best to minimise key uncertainties. The supporting documentation will cover the specific aspects outlined above, such as predictive techniques for quantifying the risk of groundwater pollution from specific UCG operations, and recommendations for 'defensive' UCG process design minimising the risk of pollution to overlying aquifers and the surface water environment. As in other groundwater protection scenarios, they key to achieving the required assessment in the GERAF is the application of the 'source-pathway-receptor' model. The receptors are obviously freshwater aquifers and surface water bodies. As regards to the sources, the most notable pollutants considered are Phenols Benzene and Polycyclic aromatic hydrocarbons [28]. These compounds are typified by low solubility, and a strong tendency towards being sorbed onto cay minerals, iron oxides and activated carbon surfaces – all of which are likely to be abundant in UCG voids.

Potential mechanisms of upward migration of pollutants are likely to vary over the life of a UCG operation. Although cross-measures transport through undisturbed strata is unlikely, given the common preponderance of low-permeability mudstones in coal seam roof measures, fracturing due to strains induced by UCG can alter the properties of the superincumbent strata. This is not only an important topic for pollution control, but also for surface subsidence prediction and mitigation. Previous mining experience provides valuable information for predicting influences of UCG on overlying strata [29].

2.5 Life Cycle sustainability assessment of the integrated UCG-CCS system

Imperial College has already developed life cycle inventory (LCI) models for alternative coal and natural gas power generation with and without CO_2 capture and storage. The existing models include alternative coal and natural gas combustion and CO_2 capture process options, pipeline transportation, injection, and saline aquifer storage, as well as coal mining, and natural gas production and supply [30, 31, 32, 33]. All LCI models developed are at unit process level and can trace all the emissions to individual unit process.

One of the objectives of the TOPS project is to develop life cycle inventory models for the UCG processes and alternative syngas utilisation options with and without CCS at unit process level. The LCI models will trace/quantify all important environmental emissions from UCG and across syngas utilisation options to their final release to the air, water and soil environmental compartments. The UCG LCI model will account for coal seam quality, panel design parameters, and UCG process operational parameters. The model will also endeavour to quantify the potential emissions to surrounding strata with input from the environmental impact assessment research carried out within the project. The coal utilisation efficiency for different chains will also be compared in the life-cycle perspective. The LCI models developed at unit process level will then be used to build the life cycle costing models in order to assess the costs of different syngas utilisation options for the integrated UCG-CCS systems and to identify opportunities to reduce costs.

3. Conclusions

Reactor zone carbon storage, as proposed by some researchers, may have some advantages, however, the problems associated with cavity storage may outweigh its potential benefits, noting that the cavity itself is likely to be disturbed and may be difficult to characterise before CO_2 storage commences; that CO_2 is likely to interact with other coal gasification products complicating potential environmental impacts and that considering the inherent uncertainty in subsurface operations, could substantially complicate CO_2 storage efforts. Most importantly, this storage potential, even if it were available, could be orders of magnitude smaller than the capacity required to store the CO_2 tonnage produced during the UCG process. Additionally, the potential CO_2 storage capacity would only be available after the end of the gasification operation, rendering on site coupled UCG-CCS rather difficult in many geological settings.

Therefore, the TOPS project is set up to develop a generic UCG-CCS site characterisation workflow, and the accompanying technologies, which would offer technological solutions to the source sink mismatch issues that are likely to be faced in many coalfields. The project aims at minimising the need for on-site CO_2 storage capacity as well as maximising the economic yield of UCG through value added end products.

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References

[1] Blinderman MS, Friedmann SJ. Underground coal gasification and carbon capture and storage: Technologies and synergies for low-cost, low-carbon syngas and secure storage. Lawrence Livermore National Laboratory, Livermore, CA. 2006; UCRL-ABS- 218560.

[2] Burton E, Friedmann SJ, Upadhye R. Best Practices in Underground Coal Gasification. Lawrence Livermore National Laboratory. 2007; http://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/ BestPracticesinUCG-draft.pdf.

[3] Kempka T, Nakaten N, Schlüter N, Azzam R. Economic viability of in-situ coal gasification with downstream CO_2 storage. Mining-Reporter 2009; 1:43-50.

[4] Roddy DJ, Younger PL. Underground coal gasification with CCS: a pathway to decarbonising industry. Energy &Environmental Science 2010; 3:400-407.

[5] Kempka T, Fernandez-Steeger T, Li D, Schulten M, Schlüter R, Krooss BM. Carbon dioxide sorption capacities of coal gasification residues. Environmental Science and Technology 2011; 45(4): 1719-1723.

[6] Kempka T, Tian H, Klebingat S, Schlüter R, Hamann J, Deowan SA, Krooss BM, Ziegler M, Azzam R. Carbon dioxide utilisation for carbamide production by application of the coupled UCG-Urea process. Energy Procedia 2011; 4:2200-2205.
[7] Nakaten N, Kempka T, Schlüter R, Hamann J, Islam R, Azzam R. Utilisation of the energy-independent underground gasification/urea process for carbamide production. Mining-Reporter 2011; 2:38-43.
[8] Mastalerz ME, Droniak A, Parke M, Rupp J. Site evaluation for subsidence risk, hydrology, and characterization of Indiana coals for Underground Coal Gasification (UCG). West Lafayette: Center for Coal Technology Research; 2011.
[9] DTI. Cleaner technology programme progress report. UK Department of Trade and Industry, DTI/Pub; 2001. Contract No.: URN 01/937
[10] DECC. Development of Underground Coal Gasification for Power Generation. UK Department of Energy and Climate Change, Contract No.: C/07/00378/00/00 URN 09D/679; 2009.
[11] Pana C. Review of underground coal gasification with reference to Alberta's potential; Energy Resources Conservation Board, ERCB/AGS, Open File Report 2009-10; 2009. 56 p.
[12] SPEA. Viability of Underground Coal Gasification with Carbon Capture and Storage in Indiana. V600 Capstone Report. School of Public and Environmental Affairs, Indiana University; 2011.
[13] Bhutto AW, Bazmi AA, Zahedi G. Underground coal gasification: From fundamentals to applications. Progress in Energy and Combustion Science. 2013; 39:189-214.
[14] DNV, 2010, Guideline for Selection, Characterization and Qualification of Sites and Projects for Geological Storage of CO_2, Report No.: 2009-1425, CO2QUALSTORE.
[15] NETL. Best practices for site screening, site selection, and initial characterization for storage of CO_2 in deep geologic formations. 2010. f http://www.netl.doe.gov/File%20Library/Research/Carbon%20Seq/Reference%20Shelf/BPM-SiteScreening.pdf
[16] Carpenter M, Kvien K, Aarnes J. The CO2QUALSTORE guideline for selection, characterisation and qualification of sites and projects for geological storage of CO_2. International Journal of Greenhouse Gas Control 2011; 5: 942-951.
[17] Gąsiewicz A, Bos C, Czapowski G, Evans D, Górecki W, Hajto M, Holliday DW, Holloway S, Jones NS, Kasiński JR, Kępińska B, Kramers L, Laenen B, Lott GK, Lokhorst A, Mathiesen A, May F, Rowley WJ, Schmidt S, Sedlacek R, Seibt P, Simmelink E, Tarkowski R, Uliasz-Misiak B, Van Wees JD, Wildenborg A, Wolfgramm M, Wong TE. Applied geology. In: Doornenbal JC, Stevenson AG (editors): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 2010; 283-299.
[18] Dill HG; Sachsenhofer R; Grecula P; Sasvari T, Palinkas L; Borojevic-Sostaric S, Strimic-Palinkas S, Prochaska W, Garuti G, Zaccarini F, Arbouille D, Schulz H-M. The origin of mineral and energy resources of Central Europe. In: The Geology of Central Europe : Vol. 2. Mesozoic and Cenozoic. Ed.: McCann T. London: Geological Society Publishing House; 2008. p. 1341-1449
[19] Yang L. Study on the model experiment and numerical simulation for underground coal gasification. Fuel, 2012; 910:40-50.
[20] Li Y. An overview of the Chinese UCG programme. Data Science Journal, 2007; 6(11); S460-66.
[21] Stańczyk K, Smoliński A, Kapusta K, Wiatowski M, Świądrowski J, Kotyrba A, Rogut J. Dynamic experimental simulation of hydrogen oriented underground gasification of lignite. Fuel, 2010; 89: 3307-3314.
[22] Stańczyk K, Howaniec N, Smolinski A, Swiadrowski J, Kapusta K, Wiatowski M, Grabowski J, Rogut J. Gasification of lignite and hard coal with air and oxygen-enriched air in a pilot scale ex-situ reactor for underground gasification. Fuel, 2011; 90: 1953-1962.
[23] Stańczyk K, Kapusta K, Wiatowski M, Świądrowski J, Smoliński A, Rogut J, Kotyrba A. Experimental simulation of hard coal underground gasification for hydrogen production. Fuel, 2012; 91: 40-50.
[24] Staúczyk K, Świądrowski J, Kapusta K, Howaniec N, Cybulski K, Rogut J, Smoliński A, Wiatowski M, Kotyrba A, Krause E, Tokarz A, Grabowski J, Ludwik-Pardała M, Bruining J, Eftekhari AA, Schuster A, Solcova O, Svoboda K, Soukup K, Landuyt P, Garot D, Śpiewak T, Szarafiński M, Niewiadomski M, Budynek P, Bednarczyk AJ, Marek A, Rzepa S, Rogosz B, Green M, Palarski J, Strozik G, Falshtynky V, Dychkowsky R. The hydrogen-orientated underground coal gasification for Europe EU RFCS Contract No RFCR-CT-2007-00006, 2012. Final Report.
[25] Kapusta K, Stańczyk K. Pollution of water during underground coal gasification of hard coal and lignite, Fuel, 2011;90:1927-1934.
[26] Britten JA, Thorsness CB. CAVSIM Underground Coal Gasification Program. 1989.
[27] Perkins G. Mathematical modelling of underground coal gasification. PhD Thesis, University of New South Wales; 2005.
[28] Younger PL, Gonzalez G, Amezaga JM. Water Management Issues in the Underground Gasification of Coal and the Subsequent Use of the Voids for Long-Term Carbon Dioxide Storage. In: Wolkersdorfer C, Freund A (editors) Mine Water and Innovative Thinking. Proceedings of the Symposium of the International Mine Water Association, Sydney, Nova Scotia. 2010: 67 – 70.
[29] Younger PL. Hydrogeological and Geomechanical Aspects of Underground Coal Gasification and its Direct Coupling to Carbon Capture and Storage. Mine Water & the Environment, 2011; 30: 127–140. (DOI 10.1007/s10230-011-0145-5).
[30] Nie Z. Life Cycle Modelling of Carbon Dioxide Capture and Geological Storage in Energy Production. PhD Thesis, Imperial College London. 2009.
[31] Korre A, Nie Z, Durucan S. Life cycle modelling of fossil fuel power generation with post-combustion CO_2 capture, International Journal of Greenhouse Gas Control, 2010; 4(2): 289-300.
[32] Nie Z, Korre A, Durucan S. Life cycle modelling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO_2 capture, transport and injection processes. Energy Procedia, 2011; 4: 2510-2517.
[33] Nie Z, Korre A, Durucan S. Full chain analysis and comparison of alternative gas-fired power plants with CO_2 capture and storage with clean coal alternatives. Energy Procedia, 2013;37: 2840-2847.